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FLIGHT TEST OF AN INTEGRATED TDMA DATA LINK/ LORAN-C NAVIGATION AND SYNCHRONIZATION SYSTEM

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An integrated computer program for TDMA data link synchronization and position determination from Loran-C and data link signal times-of-arrival was written for an IBM 4π computer and flight tested. The primary intent was to verify on a small scale in the "real world" a simulation being used in development of the technique. Results highlighted the importance of measurement geometry and synchronization problems when using overland Loran-C.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

SECTION I

INTRODUCTION

OBJECTIVE

The Electronic Grid Integration Program is an analytical and experimental effort to develop and evaluate techniques for achieving improved relative position registration between tactical elements that use different navigation systems through exploitation of the inter-element range information inherent in the operation of a time division multiple access reporting and control data net linking them.

BACKGROUND

Efficient control of aircraft in modern tactical missions requires accurate and timely knowledge of aircraft position and status. The requirements on capacity and timeliness in operations involving several hundred aircraft can be adequately met only by automatic digital data link reporting of position and status information derived by direct automatic readout from the on-board navigation system(s). There are several navigation aid systems in use by various USAF aircraft which can serve as the sources for the position information. Though derived from different sources, the position information transmitted in the common data net must all be in a common reference coordinate system. In addition to the usual "internal" errors typical of the individual navigation systems and the errors in coordinate conversion, use of different source systems by different aircraft leads to increased relative position error because of registration errors between systems. For example, the position computed from two colocated Loran-C receivers or two colocated Omega receivers would be expected to agree but not necessarily to agree with the position computed from the other system.

If the elements using these diverse navigation systems are linked by a synchronous time division multiple access data net, such as SEEK BUS, in which each unit carries a synchronized clock, then each has available not only the reported position of other elements in the data net but also the ranges to those elements as represented by the time-of-arrival of the data link position report messages. The position reports and associated range measurements provide a means for improving the relative position registration. If enough of these reports are available, they constitute, in fact, a secondary navigation system. The techniques for combining this additional navigation information with that from the primary on-board navigation

systems in such a way as to improve relative position registration is the subject of study of this program.

The problem has two basic facets. First, there is the problem of determining the optimal manner of combination of a set of redundant dissimilar measurements to obtain the best estimate of the variables (position coordinates). Second, there is the problem of the control of the interaction or feedback which inevitably results when data net members reciprocally use each other as navigation sources.

TECHNIQUE DESCRIPTION

In order to participate in the time division data link, each terminal must synchronize a local clock to the data link time standard by observing the times-of-arrival of messages from other units already synchronized and participating in the net. These other units may be ground reference units at surveyed locations or they may be other aircraft. In either case, the position of the unit transmitting is contained in the data link message and is available to the receiving unit. If the local terminal position is known, data terminal synchronization is rather straightforward and requires the observation of signals from only one other data link source, the position information being used to remove the radio propagation delay. With no prior knowledge of position, it is possible to achieve synchronism by observation of signals from at least three sources. The computations necessary to this type of passive time determination and local clock synchronization are essentially identical to those used to determine position from such synchronized navigation systems as Omega, Loran, and Navigation Satellite Systems.

In an integrated avionics system wherein the navigation instruments and the data link terminal have been interconnected for purposes of position reporting on the data link, the data link terminal may make use of the local position information computed by the navigation system to aid in synchronization (as, for example, when the minimum three data link sources are not received) or the position computation and synchronization computations could be combined in an integrated navigation/data link computer. The commonality of the algorithms for the two processes (data link synchronization and position computation) suggests that considerable computer space could be saved by such an integration. The similarity of the input data (times-of-arrival of either radio navigation aid signals or data link signals) suggests the possibility of combination of the input data themselves in a "single pass" position/synchronization computation in a common Kalman filter processor. Signals from the navigation system would be

used to aid data terminal synchronization and data link signals would be used to aid navigation.

PROGRAM OUTLINE

The Electronic Grid Integration Program was undertaken to develop and test this concept. Initial development and test of the combined navigation/synchronization algorithm was conducted in a computer simulation.

Briefly, the simulation accepts as inputs the positions of fixed elements and path specifications for moving elements, At each multiple of a specified time increment (cycle time) after startup, the program computes for each navigating element the true range to all other elements, adds a random variable and bias to account for measurement noise and source clock error, and delivers these as measurements to a position computation routine. This routine reverses the process and performs the multilateration computations on the "measurements" to determine system time and own position for each simulated unit. Source positions used in this multilateration process are the "reported" or last computed position for those sources that are themselves navigating, not the true position used by the data generation section of the program. Finally the computed time and position of each element are compared to the true time and position and error statistics are compiled. This simulation was used for intital development and test of the basic time and position computation algorithm and to explore the effects of various systems errors, sensitivity to system geometry, and interaction effects between users. The simulation program is described in detail in Reference 1 along with some preliminary results.

A real-time version of the time and position computation portion of the simulation was written for an IBM 4π airborne computer to demonstrate that such a program was feasible for an airborne computer and to verify that the techniques embodied in the position and time computation algorithm would, in fact, work with real inputs; i.e., verify the simulation results by showing that the simulations were repeatable in live flight tests. Once it is verified that the simulation results can be achieved with practical hardware and software, the simulation can be used to investigate systems involving larger numbers of users and greater geographical extent than available for live tests.

SECTION II

FLIGHT TEST CONDUCT

PURPOSE OF FLIGHT TESTING

The flight tests described and analyzed in this report were quite limited in scope. They were not intended to be a rigorous evaluation or proof of the benefits of the concept. Rather, they were intended to show that the simulation program could be translated to a workable real-time version that would in fact react in the manner predicted by the simulation when operated in a real-world Loran-C/ data link environment. With the validity of the simulation so verified, further investigations of larger systems of interacting users could be conducted via the simulation with confidence that the results could be extrapolated to the real world. The prime purpose of these flight tests was the validation of the simulation.

TESTBED DESCRIPTION

Figure 1 shows the geographic layout of the four ground sites in the synchronized data net. They are all at surveyed positions and within line-of-sight of each other. The master site at Bedford had, in addition to the data link terminal, a data recording facility to record all messages on the TDMA data net. The master site was also provided with a Loran timing receiver which could be phase-locked to the Loran-C master signal to provide time reference pulses to the data link master terminal. Thus, the data link master timing source was slaved to the Loran-C time standard. The other three ground reference sites derived time from the data link signals of the data link master and were, therefore, indirectly slaved to Loran-C time standard. The ground data link sites were, in effect made to be additional Loran-C slaves operating at the 970 MHz data link frequency.

The C-131 test aircraft was flown in the flight path shown in Figure 2. It was equipped with a data link terminal and a Teledyne Systems Company Loran-C receiver connected to deliver Loran-C time difference data and a synchronized GRI strobe to the data link terminal. Position reports were transmitted once per second on the data link and recorded at the Bedford ground terminal. Position and time were computed from any combination of sources as specified by operator entry. Position computation on Loran-C alone, data link alone or any combination of specific Loran-C and data link sites was controlled simply and solely by specifying the sites to be used. No changes to logic flow of the program were needed. Transitions between source systems

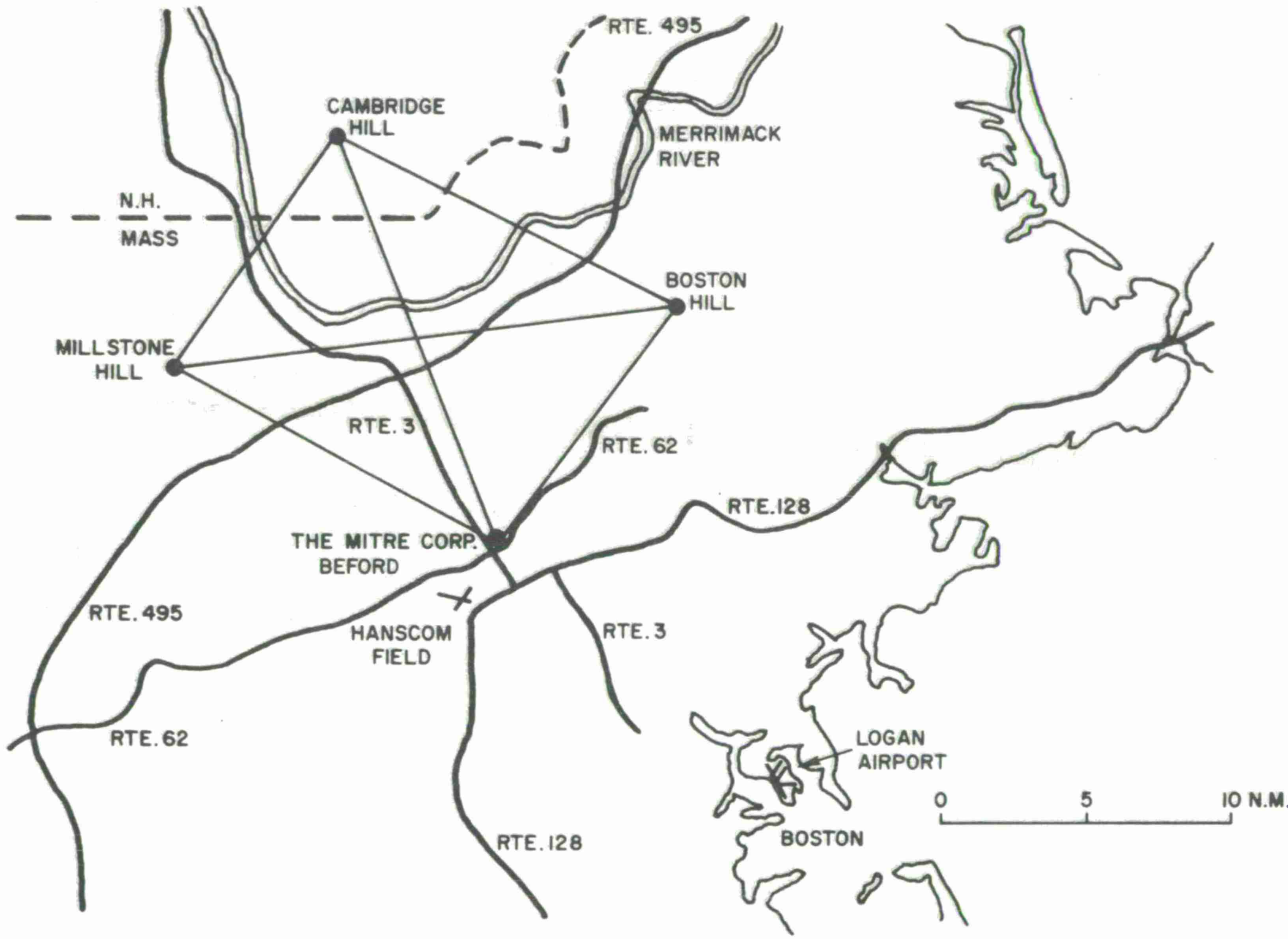

Figure 1 GROUND DATA LINK SYSTEM

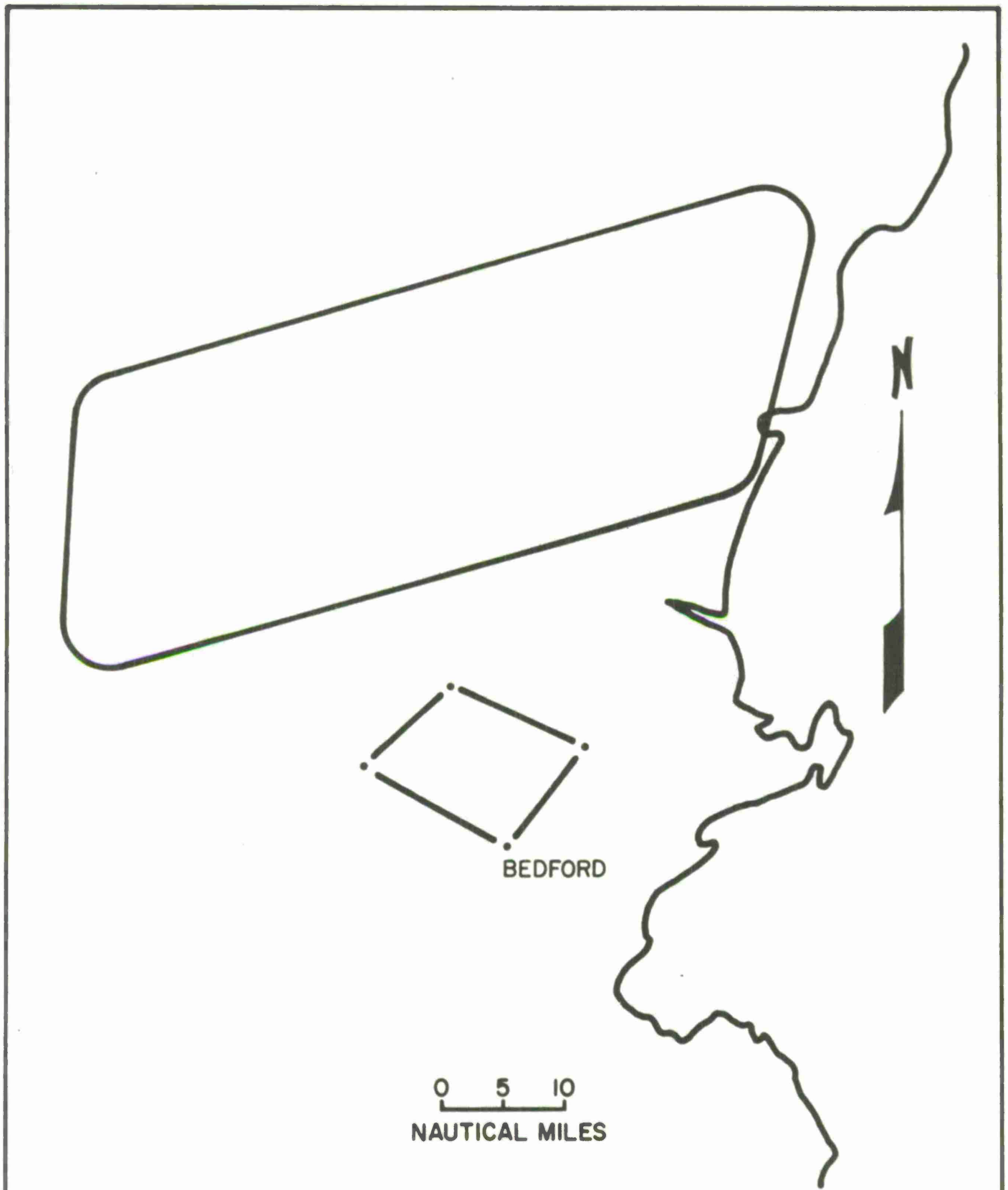

Figure 2 FLIGHT PLAN

were handled smoothly by the Kalman filter logic.

The airborne terminal also transmitted a special "beacon" signal and several special data messages once per second. Each of the four ground sites measured the time-of-arrival of the beacon signal on their synchronized local clocks and transmitted these TOA data to Bedford for recording. The recorded times-of-arrival were then processed in a Post Mission Analysis Program (PMAP) to compute an independent estimate of aircraft true position. This position is independent of the time or position estimates made by the aircraft. This system had been shown in previous calibration flights to produce position accuracies of 100 to 200 feet relative to the ground system. The special data messages contained internal program parameters of use in analysis.

In the computer program used in this exercise, a nominal overland propagation velocity of the Loran-C signals is used for all paths because all test flights were conducted over land and therefore all propagation path length changes were within the final overland portions of each path. The position bias that results from applying the overland velocity to the entire length of paths containing appreciable sea surface (see Figure 3) was removed by adjustment of the emission delay correction for each slave. This was done simply by operating the Loran-C receiver and computer at a known fixed point (the Bedford site) and adjusting the emission delay corrections empirically until the computed position matched the known position. This procedure obviously corrects for all errors, even local anomalies, at that one point. The correction will not necessarily be correct at other points in the area because of local anomalies and changes in the land/sea ratio in the path from different locations within the test flight area. The resulting "grid warp" was, in fact, detected and resulted in Loran-C position errors of as much as one-half nautical mile relative to the calibration point at some points on the flight path. No attempt was made to correct these errors by mapping techniques. Dynamic correction through combination with data link range measurements was one of the points of interest to the investigation.

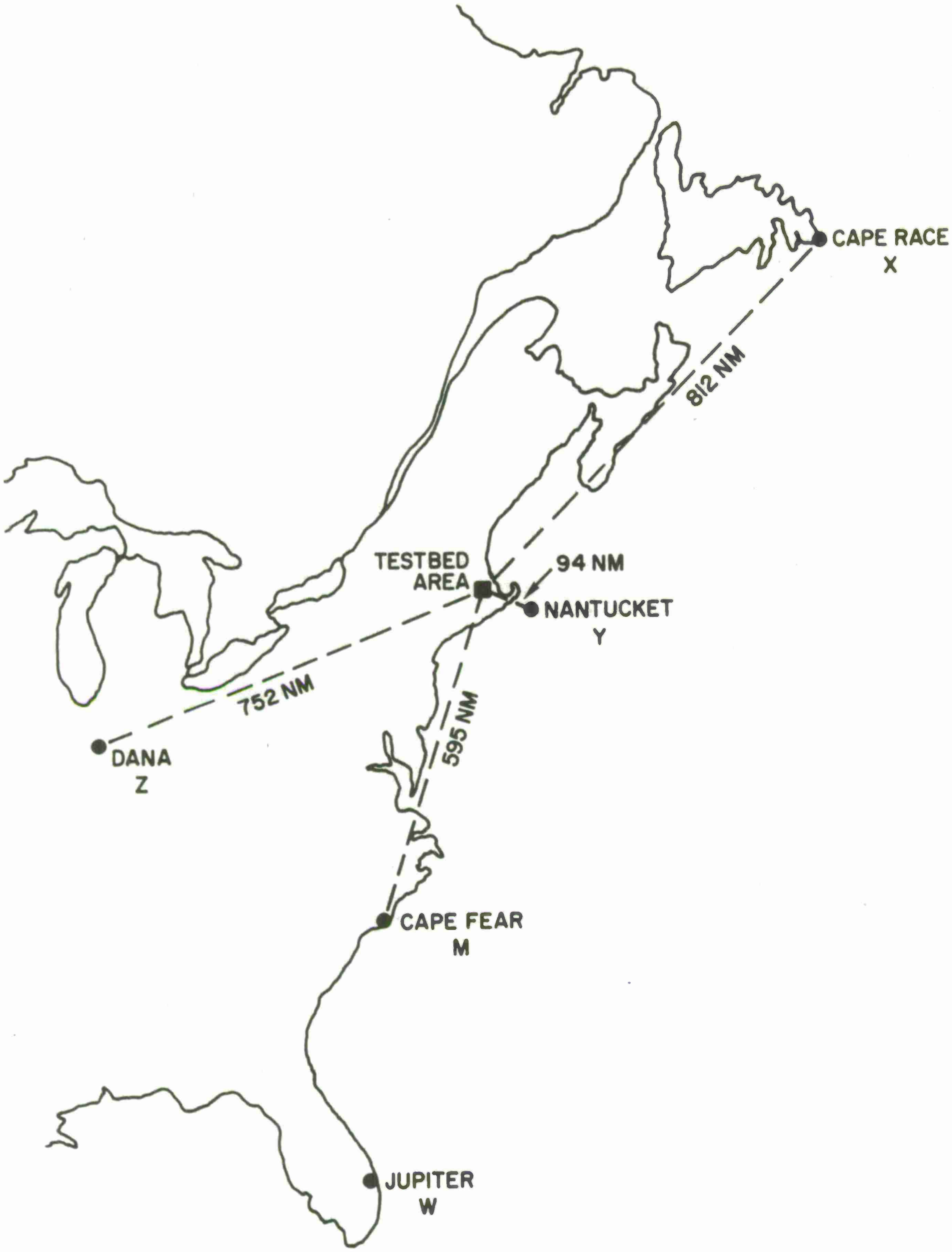

Figure 3 EAST COAST LORAN C CHAIN

SECTION III

FLIGHT TEST RESULTS

GENERAL

The flight tests confirmed and validated the simulation in all important respects. The combination program was able to obtain and maintain data link synchronization and compute position based on any combination of Loran-C and/or data link ranging measurements so long as at least three sources were available. When only Loran-C sources were available, the program becomes essentially the familiar direct ranging loran (DRL) with its advantages of decreased GDOP and the ability temporarily to navigate on only two sources. When measurements from the range-capable synchronized data link were added there was in general a noticeable improvement in position variance resulting from the inclusion of data with less measurement noise. Reruns of live flight test segments on the simulation produced essentially the same results as observed during the live tests. The ability of the same navigation/synchronization technique embodied in the simulation to operate in an airborne computer with real-time inputs has been confirmed.

The preceding should not, however, be construed to mean that the combination of Loran-C and data link measurements as implemented always resulted in a clearly valuable improvement in position accuracy. The position variance was always improved when data link signals were combined with Loran-C in the position determination but certain types of bias errors were frequently left largely unaffected.

The situations analyzed in detail in the following pages were selected to illustrate the limits of performance. Analysis of the response in these cases provides the greatest insight into the operation of the system.

GEOMETRICAL DILUTION OF PRECISION (GDOP)

The error in computed position resulting from a trilateration operation will, in general, be greater than the errors in the range measurements by a factor called GDOP. It is related to the angles subtended at the user position by the baselines of the reference site system used to derive the measurements.

The reference sites of the ground data link system in the testbed area provided baselines of less than 20 nautical miles each. The observed GDOP, therefore, increases rapidly as an aircraft travels

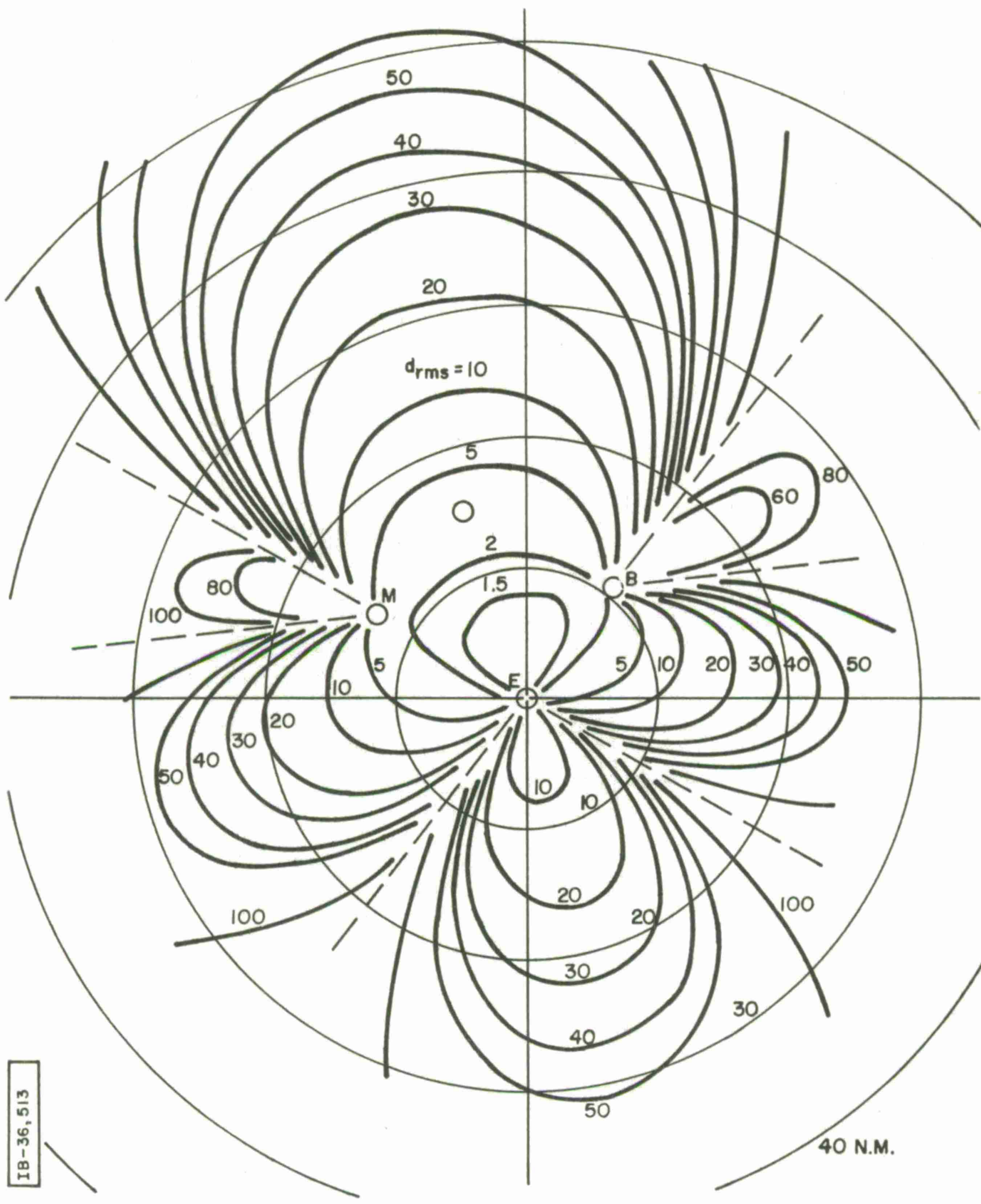

Figure 4. HYPERBOLIC GDOP, THE RATIO
OF POSITION ERROR TO MEASUREMENT ERROR

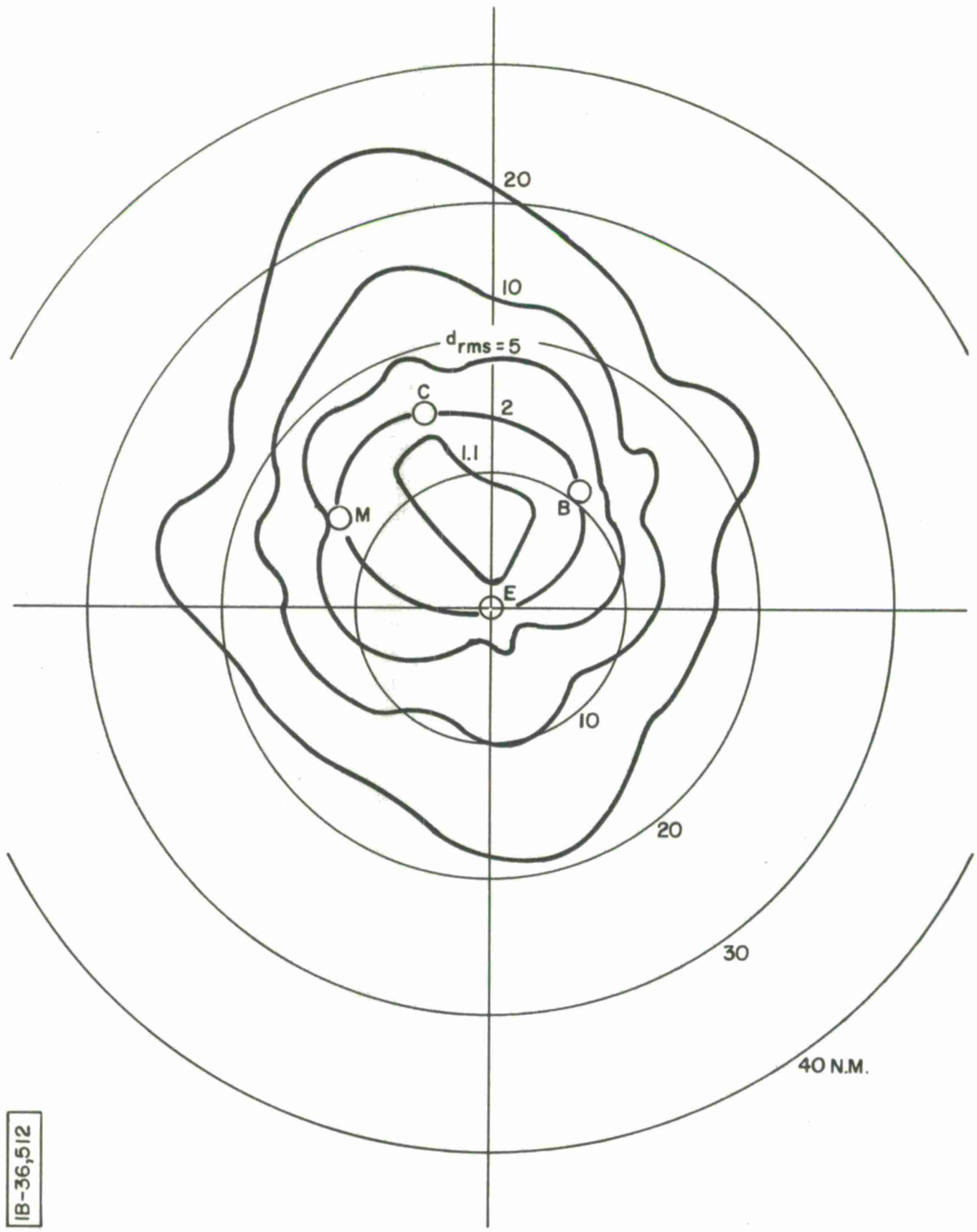

Figure 5 FOUR-SITE NORMAL MODE GDOP

away from the ground site complex. Figures 4 and 5 are maps of the ground data link system overlaid by the resulting GDOP contours. The numbers on the contour lines indicate the magnitude of amplification of measurement errors. For example, at a position 45 nautical miles north of Bedford, an error of 0.1 microsecond in measurement of signal time of arrival (TOA) will produce a position error of approximately 5000 feet (GDOP=50).

The GDOP provided by the East Coast Loran-C chain in the test area is much smaller and very nearly constant. Selection of Cape Race and Nantucket as the slave pair results in a GDOP of 1.3. The GDOP for the Nantucket-Dana pair varies from 1.8 to 3.5 over the course of the flight path. For comparison, the minimum data link GDOP on this flight path is 8. It goes to infinity on baseline extensions at the eastern and western ends; if only the three main ground sites are used.

On the other hand, the measurement accuracy expected from overland Loran-C is generally inferior to that of a microwave line of sight ranging system because ground wave propagation over inhomogenous paths is not uniform and not as well understood. A previous report (Reference 2) revealed a pronounced Loran-C grid warp in the test area. Figures 6 and 7 offer an interesting comparison. Figure 6 is reprinted from Reference 2 and shows approximately 5/8 nautical mile bias in position determined from Loran-C using Nantucket and Dana as slaves. Figure 7 presents a flight path segment in this same vicinity when three data link signals alone were used for position computation. The position error here is approximately 1.1 nautical miles! However, the GDOP at this location is 45 and therefore this error could have been caused by a net relative synchronization discrepancy of only 0.15 microseconds (150 feet) between the one-way ranging measurements. Thus we see that the improvement in position accuracy to be expected from combining Loran-C and microwave ranging signals from the data link is not a clear-cut proposition but highly dependent on the geometry of the situation. We will return to this point repeatedly. The benefits to be expected from the combination of measurements from the two systems is crucially dependent on the geometry of the measurement paths.

THE UNDETECTABLE ERROR

To illustrate the dependence of the system response on the geometry of the situation, the following extreme example is presented. In Figure 8 the airborne unit was reporting a very erroneous position while navigating on Loran-C using Nantucket and Dana. The Loran-C receiver phase tracking loop for the Dana signal had settled one cycle late on the Loran-C pulse. This is an anomalous condition which

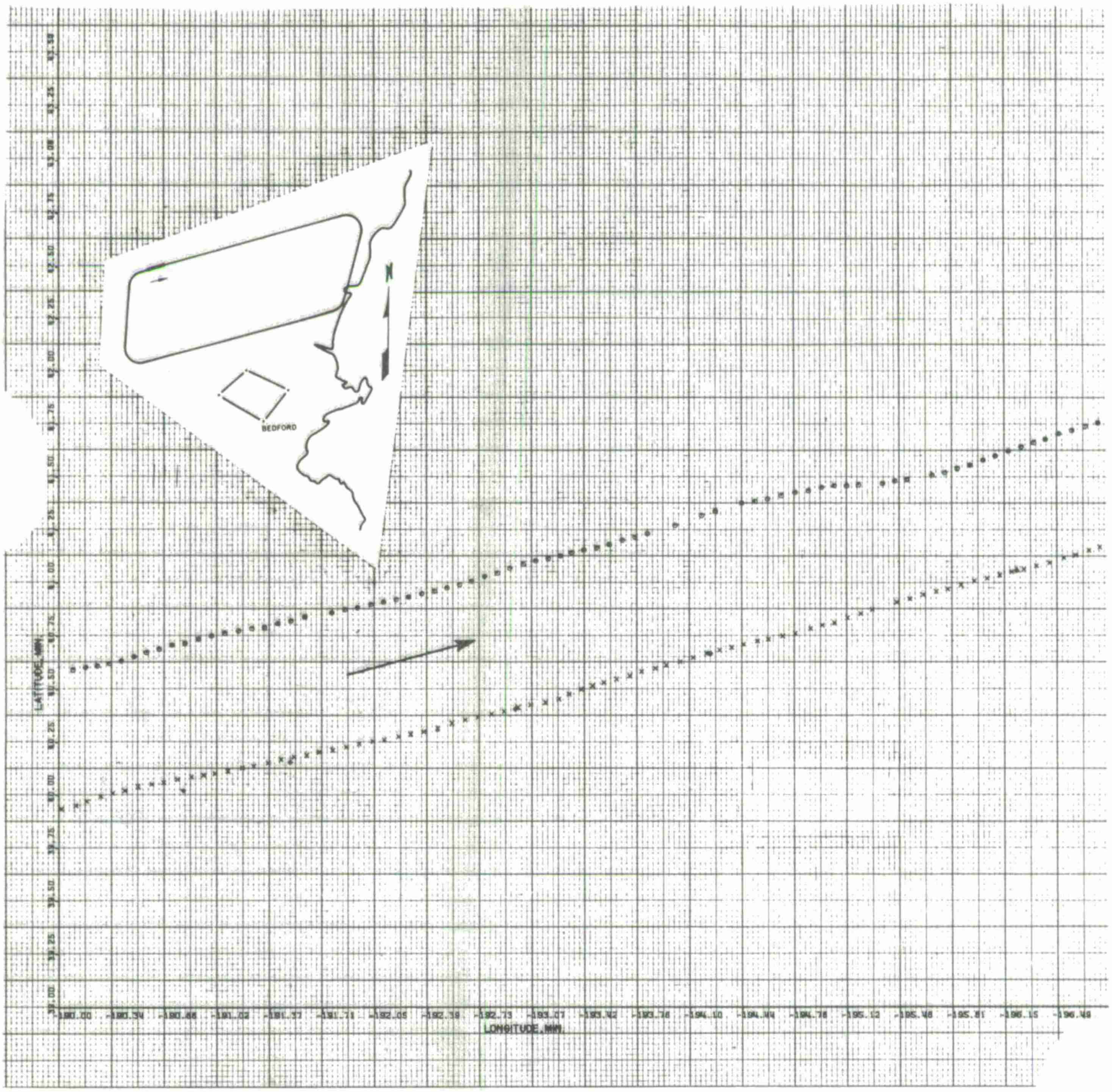

FIGURE 6. Position error in northwest corner caused by Loran-C grid warp

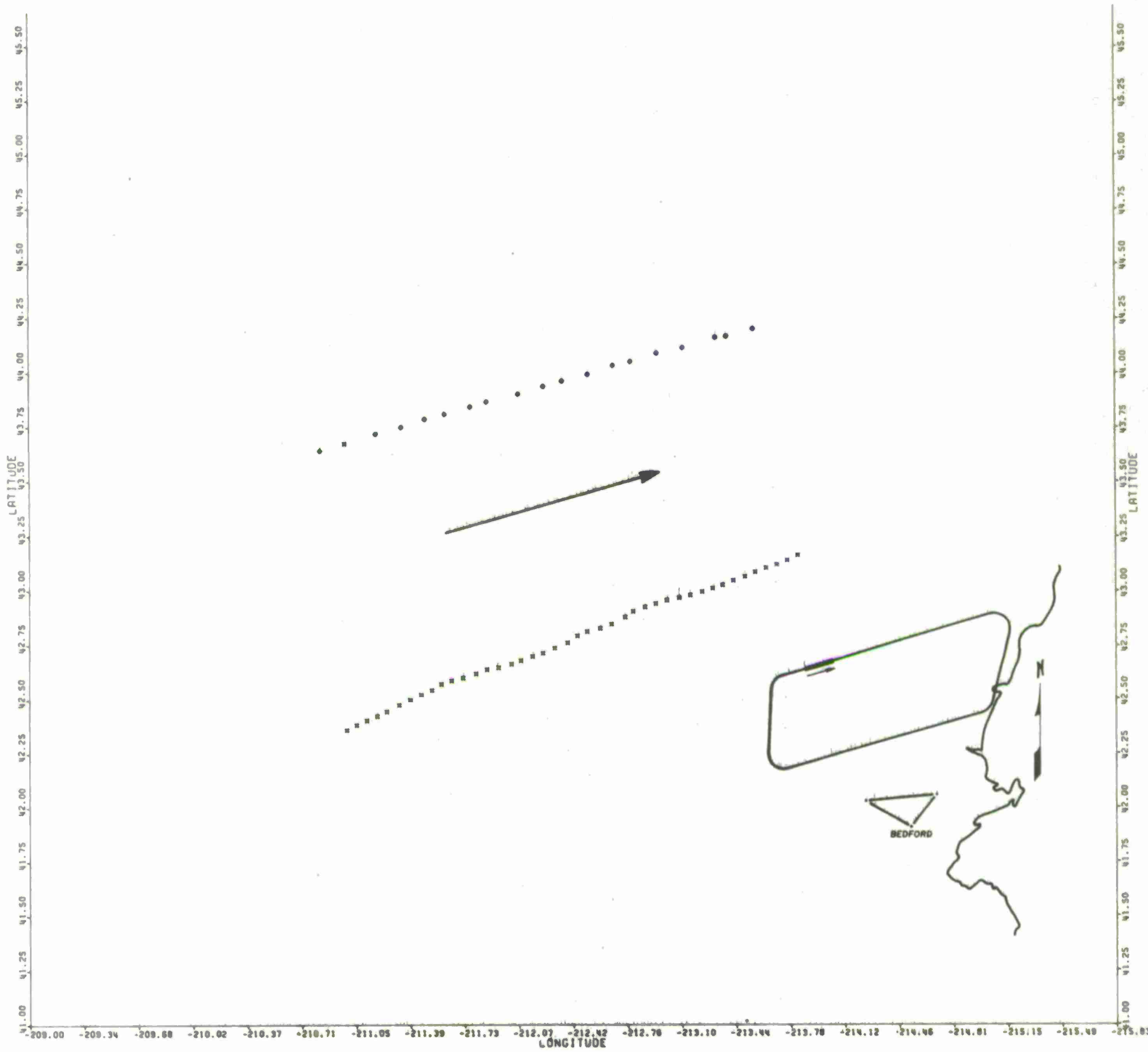

FIGURE 7. Data link navigation error resulting from high GDOP acting on small timing error

rectified itself in a short while; however, it serves admirably the present discussion because the magnitude of this known error was great enough to predominate over smaller but unascertained errors in the system.

The signal from Dana, in effect, arrived 10 microseconds late relative to its normal time of arrival at the true position of the aircraft (indicated by ◊). The navigation algorithm derived a local clock setting and a position as required to make the apparent times of arrival of the signals from all three Loran-C stations commensurate with their ranges from the computed position.

The position and clock setting found to satisfy this condition were 2.1 nautical miles due south of the true position and 13.3 microseconds late. At point A, signals from four ground data link sites were added to the measurement sample. The signals from the three data link sites appear to arrive 13.3 microseconds early; however, the assumed position is 13.0 microseconds of range nearer Bedford and Cambridge Hill, 12.2 microseconds nearer Millstone, and 12.6 microseconds nearer Boston Hill or an average of 12.7 microseconds nearer the data link ground system. The airborne terminal therefore "sees" an average of only 0.6 microseconds discrepancy between these times of arrival and the computed ranges. Combining the data from all seven sources would therefore be expected to produce a position adjustment of only about 300-500 feet northward at which point the discrepancies between the Loran-C measurements and data link measurements would be in balance. It is difficult to see such an adjustment on the plot but the point of interest is that the improvement is negligible when compared to the error.

Figure 8a is a plot of a simulation run under very similar conditions. Here, Dana was given a 7 microsecond delay resulting in a position bias of 1.75 nautical miles due south. At point A measurements from three ground data link sites simulating Bedford, Boston Hill and Millstone were added. The resulting correction was 0.25 nautical mile. This is considerably greater than in the live test and indicates the presence of some small additional error in addition to the Dana receiver tracking error in the live test. The source of the additional error is discussed in the next section. Still, the results are in agreement with the live test in indicating that the addition of three data link signals in this geometry produces only a nominal effect; i.e., the result observed in the flight test arises primarily from the geometry rather than some undetermined error in flight test conduct.

This situation is analogous to the high GDOP situation mentioned earlier wherein small measurement errors can produce large position errors. Here a large position error generates only a small corrective

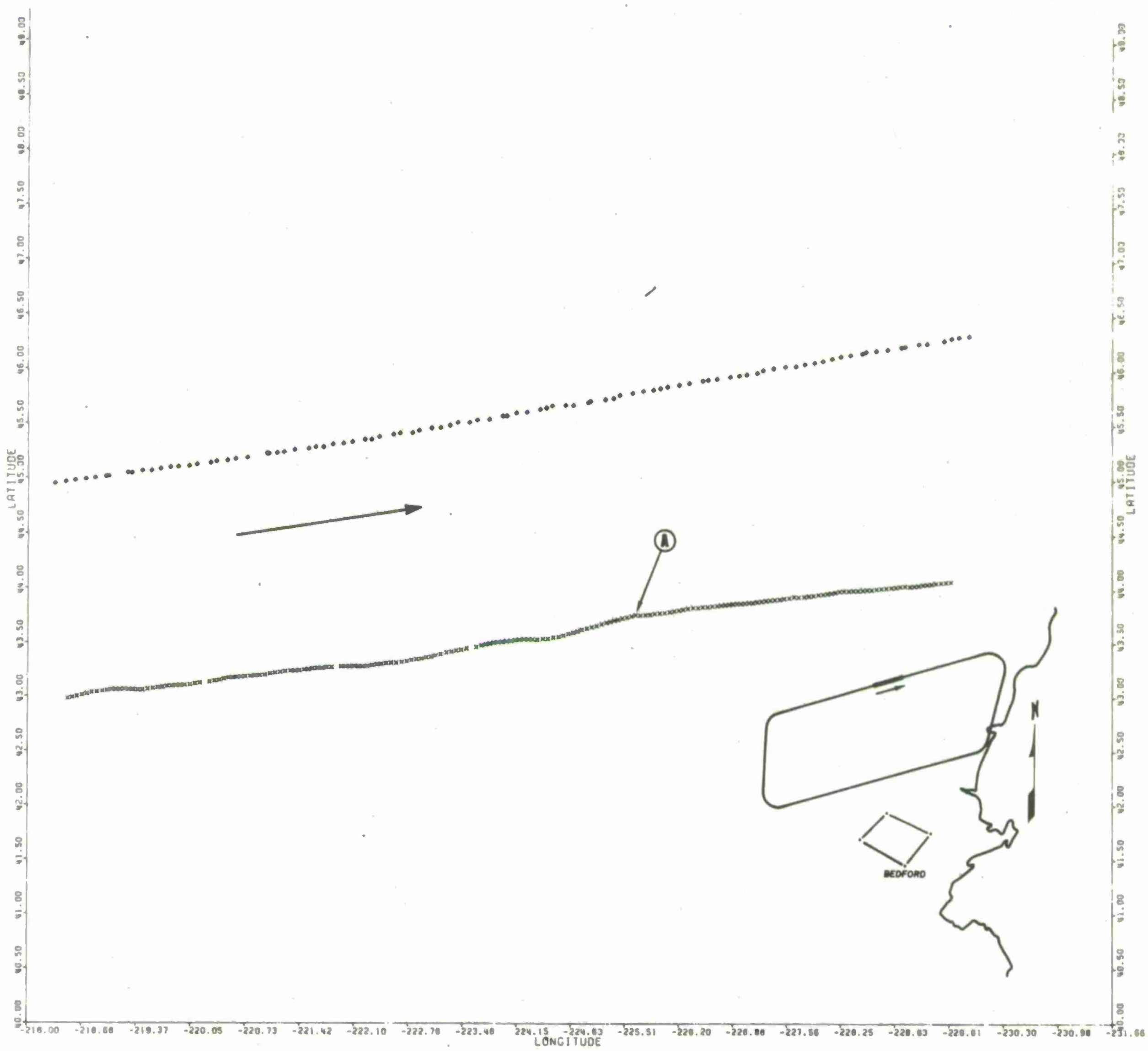

FIGURE 8. Addition of data link signals provided no improvement in bias in this geometry

FIGURE 8a. Simulation output of run similar to FIGURE 8 live test result

force again as a consequence solely of the geometry of the situation. The added measurements are from sites which lie in the same direction as the "good" measurements already available. The angles to the ground data link sites all lie within the angle subtended by the Cape Fear-to-Nantucket Loran-C baseline. The airborne unit receives little new information. The position and time computed from Loran-C alone already account for synchronized signals received from that direction. Had the data link sites been to the east or west, the new measurements would have tended to cancel the one from Dana.

Another noteworthy point is that although the measurement from Dana is known to have been 10 microseconds in error, there are no data available to the airborne computer to allow detection of the condition. There are, however, data available in the system which will allow its correction. This will be discussed in a later section on Master feedback.

In Figure 9, some 22 minutes later, the aircraft is in a rather different geometry. The data link sources now lie generally to the east of the aircraft. The aircraft position derived from Loran-C is biased to the north by about 0.15 - 0.2 nautical miles because of the propagation anomaly in the Dana signal as discussed in Reference 2. (The receiver tracking loop has by this time located the correct cycle.) Now when the data link signals are added to the sample, there is an improvement. Average position error drops from 930 feet to 575 feet. The reason for this turnabout from no improvement in a two-mile error to an improvement of over 37% is the geometry. The new measurements improve the GDOP from 1.8 on Loran-C alone to 0.8 on mixed data.

WHAT TIME IS IT HERE?

In the analyses of the foregoing two flight test segments, a known error in Loran-C position predominated. It was shown that the addition of data link ranges tended to improve position accuracy; however, the improvement to be expected is heavily dependent on the geometry of the situation. It was implied that given favorable geometry improvements would be realized. Unfortunately this was not always true as is illustrated in Figure 10. The aircraft was proceeding as shown navigating on Loran-C and three data link signals. In this example Nantucket and Cape Race were the Loran-C slaves in use. When data link signals were deleted from the navigation source set, position accuracy improved from 1650 feet error to 910 feet. In other words, the data link signals were actually harmful in terms of relative position registration between ground and airborne units. The problem here is one of system synchronization compounded by the ever present

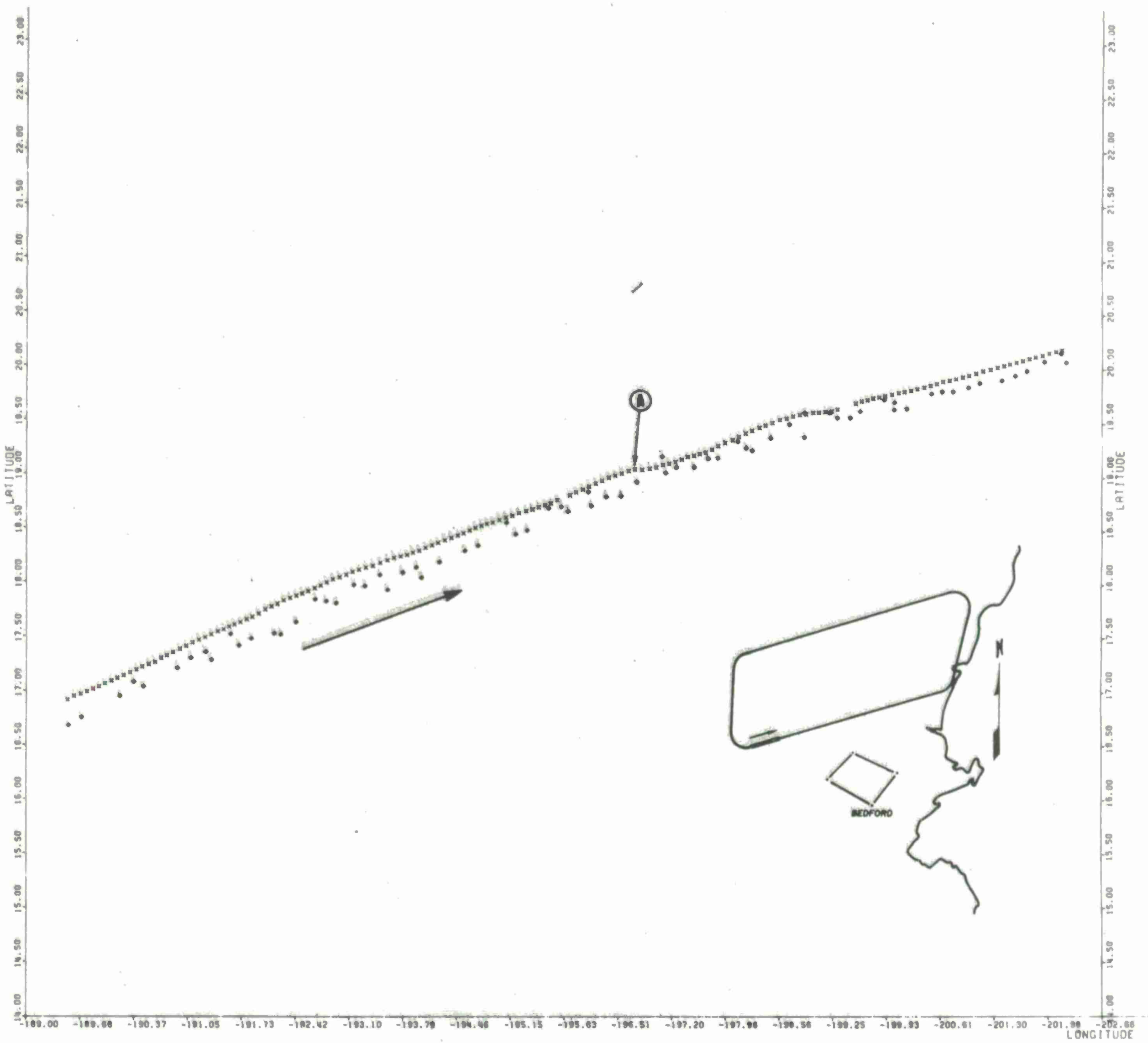

FIGURE 9. Favorable geometry allows data link signals to produce improvement

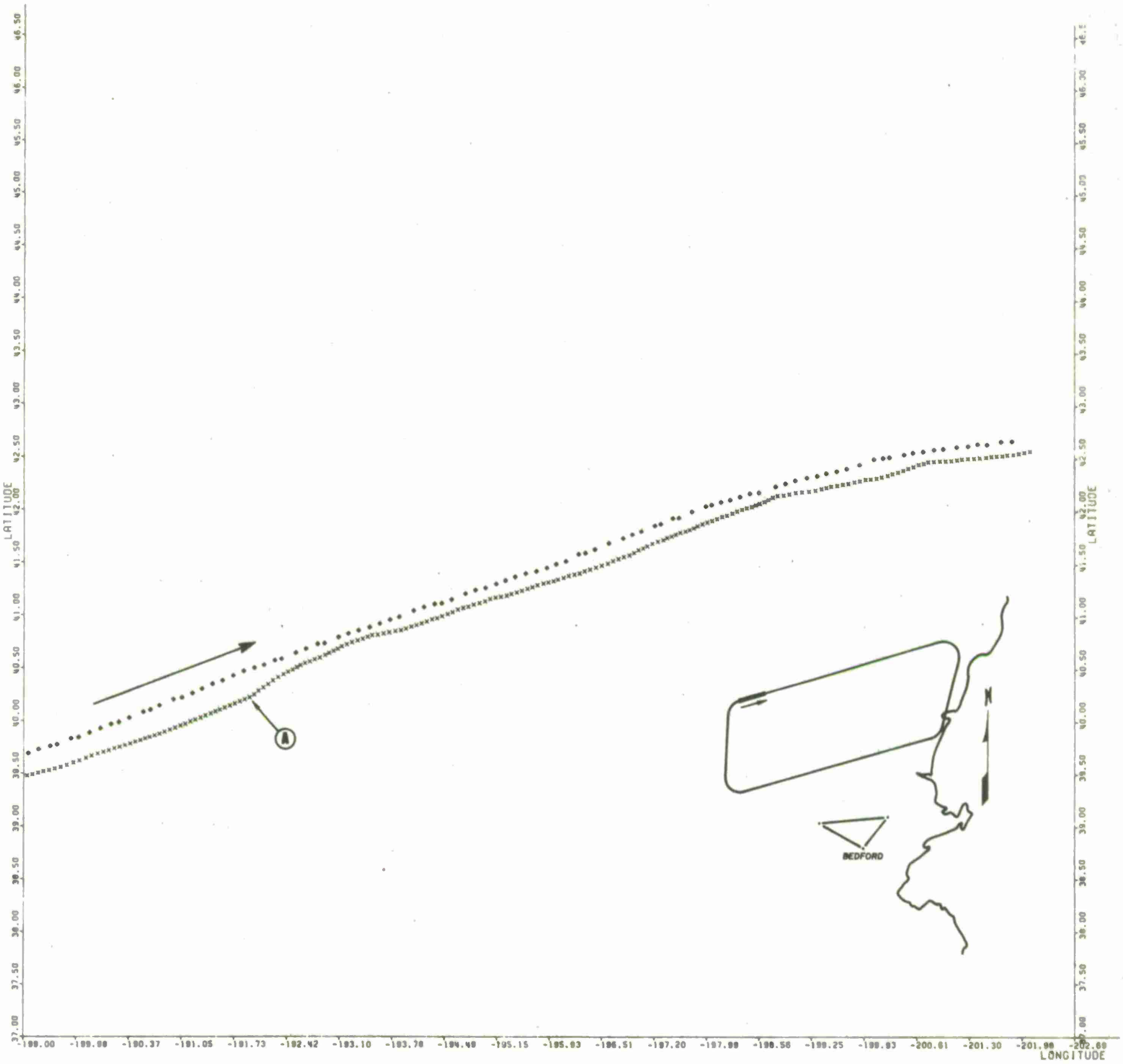

FIGURE 10. Synchronization error between ground data link system and Loran-C introduces additional position error in this example

effects of the geometry of the situation.

The airborne unit measured the times of arrival of all signals (Loran-C and data link) on a common clock. In this arrangement, the data link sites may be thought of as additional Loran-C slaves operating at microwave frequencies. This provides many advantages such as the ability to maintain navigation on any mixed set of three sources. On the other hand it means that the ground data link sources must be synchronized to the Loran-C time standard and any errors in this synchronization process are propagated into the position of users of mixed data.

The three sites of the ground data link system were synchronized to each other to within ± 0.1 microsecond by way of direct line-of-sight data link signals; however, the master data link site at Bedford was not so well synchronized to Loran-C. Analysis of data tapes indicates that during this flight the error was of the order of 0.6 microsecond. The error was (at least partially) the result of equipment misalignment at the Bedford site; however, in analyzing this effect it became apparent that the same effect can occur purely from Loran-C propagation effects.

When discussing Loran-C propagation errors, it is customary to think of errors in time difference (grid warpage) because this is what controls the computed position. The <u>net</u> effect of propagation delay differences in master and slave signal paths is the factor controlling position. The clock settings of direct ranging units are (in addition) controlled by the total delay in all paths. Errors in position and time caused by the net time difference errors (grid warpage) are correlated; that is the direction and magnitude of clock bias and position bias are interrelated and subject to improvement (to a degree controlled by the geometry) upon the addition of data link signals. The portion of clock bias caused by the total delay may result in either improvement or deterioration in relative position accuracy when data are combined depending on the relative directions of the errors.

As an example, suppose all three Loran-C signals to a certain user suffered an excess delay of 0.1 microsecond either within the Loran-C receiver or from some propagation anomaly. The computed position would remain correct but the user clock would be offset by 0.1 microsecond. One-way ranges to distant, properly synchronized data link sites unaffected by this propagation anomaly would all appear 100 feet short and the resulting position correction will always degrade accuracy. Automatic adaptive interference filters common in modern Loran-C receivers can cause the same effect.

Figure 11 is included to illustrate an instance when this error type fortuitously produced an improvement. Here addition of the data link signals at point A causes an improvement from 0.4 to 0.2 nautical miles error. At this location the improvement should have been negligible for the same reasons as explained in connection with Figure 8. The improvement in this example was caused by the same synchronization error at Bedford. The result is an improvement only because of the direction of the original error; i.e., away from the data link sites instead of nearer as in Figure 10.

MASTER FEEDBACK

In early simulation exercises involving multiple navigating units interacting via one-way data link ranging, the system was found to be unstable and strongly divergent; i.e., initially small position and time errors at one unit were magnified by GDOP at other units and fed back into the system causing larger and larger errors. Several modifications to the basic mulitlateration algorithm were developed to control this problem. Among these were master feedback, a hierarchical scheme for source selection, and the Kalman filter for weighting source data on the basis of covariance data transmitted in the source data message. All three were used in the program tested. Their operation is described in detail in Reference 3. The effect of master feedback in small systems is discussed below.

Master feedback refers to data transmitted by the data link master concerning the master's estimate of system errors. The master does not adjust either time or position; however, data is received at the master terminal which could be used for navigation. The master uses this data to compute the average system error. The discrepancies between the range to each reporting element as computed from the reported position is compared to the range as indicated by the time of arrival of the report. The errors are averaged and the average is transmitted on the data link as "time feedback". The master also computes a position correction from these ranging measurements but again, instead of adjusting position, the master transmits this data as "position feedback".

In a large system the effect is to stabilize and counteract those interaction effects between multiple users tending to produce ever larger errors (See Reference 1). In small systems, such as the live flight test system, the effect is a pronounced improvement in position accuracy even when there is no interaction between multiple navigating units.

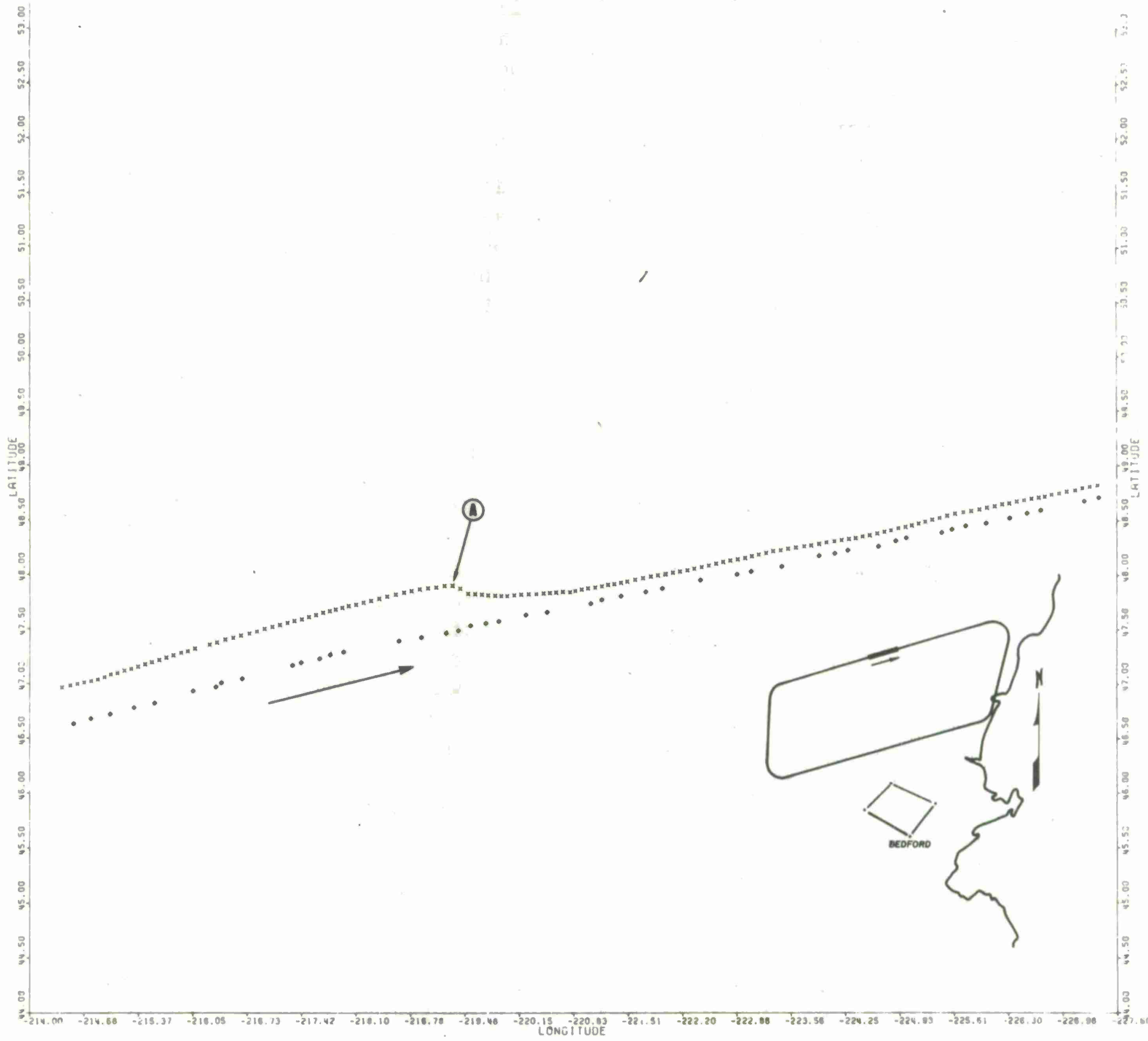

FIGURE 11. Synchronization error of the ground system caused misleading apparent improvement in this test

Figure 12 shows the effect graphically. The aircraft was proceeding west-to-east using three data link sources only. The GDOP was 46 and position error 1.1 nautical miles. At point A, the data link master started transmitting feedback messages. In this system, there is only one navigating unit capable of responding to feedback so this one aircraft is forced to modify position and time to attempt to reduce master feedback essentially to zero. Since there is only one element introducing system error and only the same one aircraft responding, the net result is the equivalent of performing time determination by a round-trip ranging operation between the navigating unit and the master. This effectively changes the position determination from an essentially hyperbolic geometry to a true direct ranging geometry. The GDOP is reduced from 46 to approximately 3. The result in this live test is just as predicted by the simulation for a single user system.

Master feedback is a powerful tool, but is effective only on units in two-way communication with the master. In larger tactical areas there will be many units not satisfying this condition. In these systems master feedback acts to stabilize and improve the accuracy of the user group within range of the master and these units in turn provide baselines and coverage for the more distant elements. Units not under control of master feedback cannot, however, be allowed to interact with each other through one-way ranging. Simulation studies have shown that the resulting instability within this group leads to a degradation in position accuracy far exceeding any advantage from measurement geometry to be gained from such interaction. This poses serious conflicts with the basic idea of an improvement in relative position registration between users of diverse navigation systems through use of one-way ranging in a TDMA data net.

There is also a question as to the proper derivation and application of master feedback in a system wherein users within coverage of the master are deriving position and time from combinations of systems other than the data link itself. Further development of this is beyond the scope of this report on live flight test. It is an area deserving further exploration via the simulation.

With master feedback, the data link was quite effective in reducing Loran-C grid warp errors. Figure 13 is typical. Without data link the Loran-C error was approximately 0.5 nautical mile northward. This was reduced to an average of 0.1 nautical mile over the segment shown.

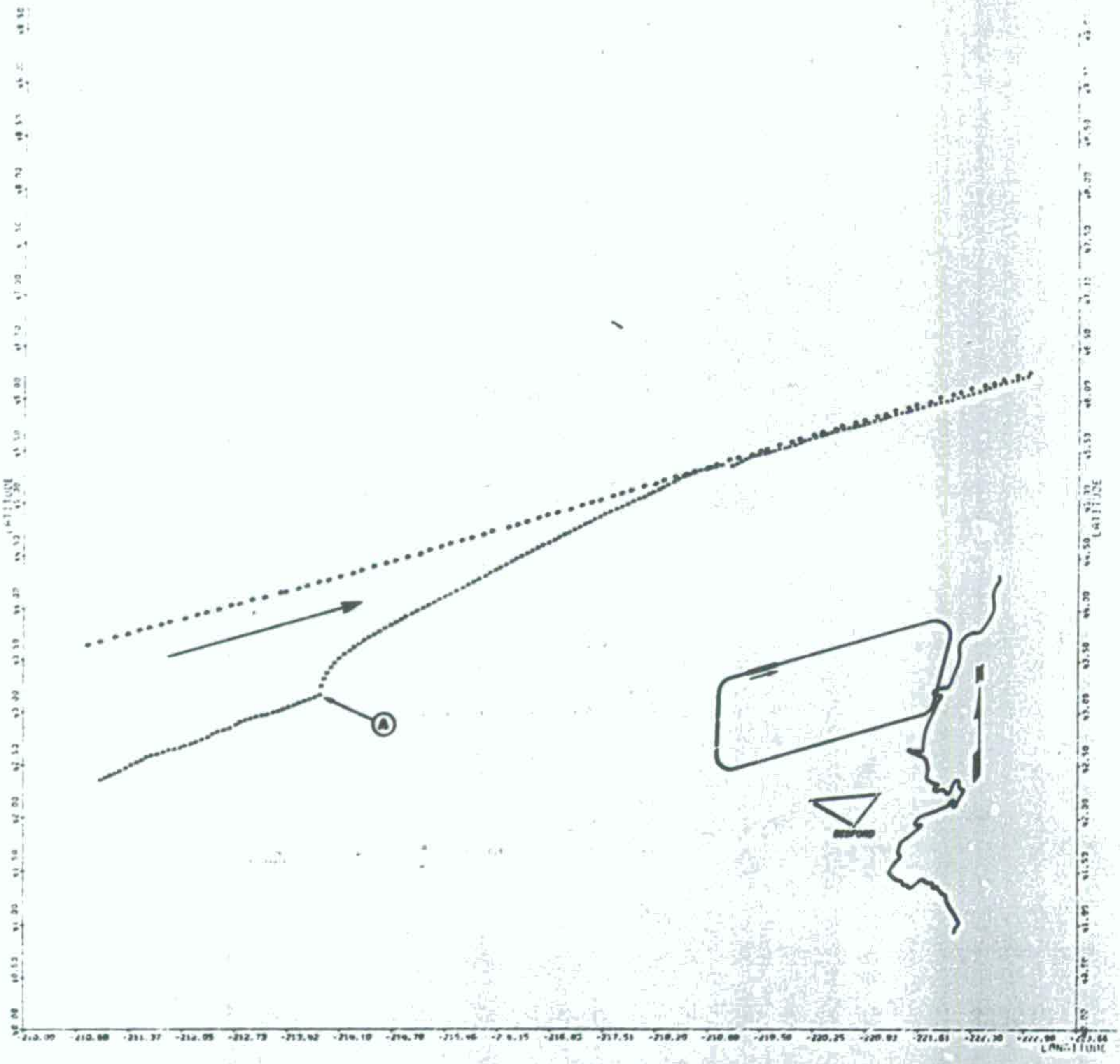

FIGURE 12. Effect of master feedback on a single user is equivalent to round-trip ranging on the master

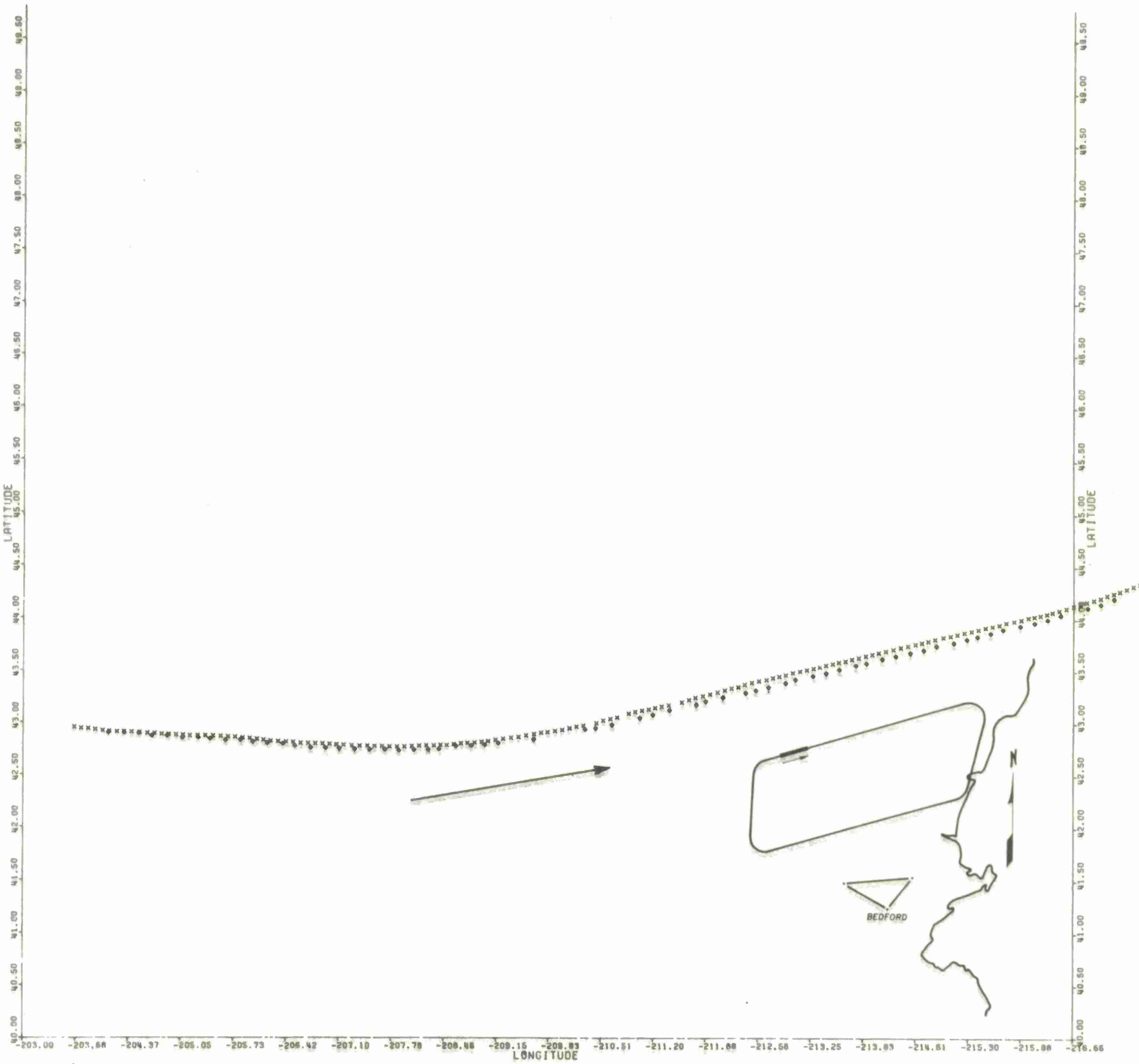

FIGURE 13. Loran-C and data link with master feedback in use

SECTION IV

DISCUSSION OF RESULTS

It was not the objective of the flight tests reported here to establish absolute navigation accuracies. That would have required a much more extensive program. The intent was an initial exploration of the application to a real-world navigation system of a technique developed in computer simulation. The results shown for Loran-C certainly are not to be taken as a statement of the tested predictable accuracy of the Loran-C system. For purposes of these tests it was desirable in many cases to leave uncorrected some system bias errors so as better to show the effects of changes in the processing of the combined data. In this way the effect of minor equipment misalignments and random noise error could be suppressed.

The results confirmed that the addition of the one-way data link ranges to the Loran-C data in a common processing algorithm was a workable technique and generally improved position accuracy over either Loran-C alone or data link ranging alone. The degree of improvement may, however, be insignificantly small for some geographic relationships between the Loran-C stations, data link sites, and the user. At the other extreme the improvement is very great if the GDOP provided by either system alone is very large as when near a baseline extension, either of the data link ground system or the Loran-C chain.

The track plots reproduced here were selected to illustrate particular attributes and responses of the system to certain situations of interest such as areas of high GDOP or large Loran-C grid warp. Correspondence of response between simulation and live test results in these cases of amplified bias is easier to verify than in those in which the errors are small, zero-mean random.

Any improvement in position accuracy relative to the use of Loran-C alone is to be expected primarily over land where the propagation of Loran-C signals is not well predictable. In the mechanization employed in these flight tests, the use of a common clock for both direct ranging loran and data link timing tends, however, to negate the potential advantage. Combination of the data in areas of Loran-C grid warp propagates Loran-C time errors into the data link system which can cause the position derived from the combined system to be more in error than that from Loran-C alone. It appears that direct integration of position and synchronization in a combined Loran-C/data link system in the manner attempted in this test will not result in realization of the full potential benefits in position